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$^{40}Ar/^{39}Ar$ geochronology of Neogene phreatomagmatic volcanism in the western Pannonian Basin, Hungary

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Abstract

Neogene alkaline basaltic volcanic fields in the western Pannonian Basin, Hungary, including the Bakony–Balaton Highland and the Little Hungarian Plain volcanic fields are the erosional remnants of clusters of small-volume, possibly monogenetic volcanoes. Moderately to strongly eroded maars, tuff rings, scoria cones, and associated lava flows span an age range of ca. 6 Myr as previously determined by the K/Ar method. High resolution $^{40}Ar/^{39}Ar$ plateau ages on 18 samples have been obtained to determine the age range for the western Pannonian Basin Neogene intracontinental volcanic province. The new $^{40}Ar/^{39}Ar$ age determinations confirm the previously obtained K/Ar ages in the sense that no systematic biases were found between the two data sets. However, our study also serves to illustrate the inherent advantages of the $^{40}Ar/^{39}Ar$ technique: greater analytical precision, and internal tests for reliability of the obtained results provide more stringent constraints on reconstructions of the magmatic evolution of the volcanic field. Periods of increased activity with multiple eruptions occurred at ca. 7.95 Ma, 4.10 Ma, 3.80 Ma and 3.00 Ma.

These new results more precisely date remnants of lava lakes or flows that define geomorphological marker horizons, for which the age is significant for interpreting the erosion history of the landscape. The results also demonstrate that during short periods of more intense activity not only were new centers formed but pre-existing centers were rejuvenated.

Keywords: phreatomagmatic; pyroclastic; basanite; monogenetic; scoria; $^{40}Ar/^{39}Ar$ geochronology; peperite; erosion

1. Introduction

Intracontinental volcanic fields commonly are characterized by low magma supply rates and prolonged activity over periods of millions of years (Walker, 1993; Takada, 1994; Connor et al., 2000). They typically consist of scattered volcanic vents that are often considered to be monogenetic as they apparently never constructed significant composite edifices (Walker, 1993). However, on closer inspection many of the vents do show signs of

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multiple eruption histories (Németh et al., 2003), and their architecture can be complex despite their small size; establishing a time line for individual centers is thus important for understanding their evolution. In addition to the smaller centers, large shield volcanoes and lava flow fields may also occur in these fields (Hasenaka, 1994). Fundamental physical characteristics of volcanic fields include 1) the number, type, eruption styles, sedimentation and erosion history of individual volcanoes (White, 1990; Németh and Martin, 1999a); 2) the timing and frequency of eruptions (Connor et al., 2000); 3) the distribution of volcanoes (Connor et al., 1992); and 4) the relationship of the volcanoes to tectonic features such as basins, faults, and rift zones (Conway et al., 1997). Characterizing such features provides information on magma generation and ascent and will provide a quantitative basis for comparisons among different volcanic fields.

The Neogene western Pannonian volcanic fields were shown during the past decade to have been predominantly phreatomagmatic in eruption style (Németh et al., 2001; Martin and Németh, 2004). Interaction of abundant meteoric water and uprising magma generated explosions that produced the maars and tuff rings. However, there is also evidence for non-explosive, peperite-forming interactions between wet host sediment and intruding, predominantly basanite melt (Martin and Németh, 2007). The resulting craters have been filled by lava in cases where the magma supply was large enough. The timing of the volcanic events in western Hungary has been a concern for a long time (Lóczy, 1913), which has been generally addressed in the last 2 decades by several studies applying the K/Ar technique (Balogh et al., 1982, 1986; Pécskay et al., 1995; Balogh and Pécskay, 2001). This work revealed that the duration of volcanism was *ca.* 6 Myrs, from about 8 Ma up to 2 Ma. The initiation of volcanism appears to be well constrained at ca 8.0 Ma by several attempts to gain precise K/Ar ages from a maar volcanic complex at Tihany (Balogh and Németh, 2005), but possible episodicity, synchroneiety, and the timing of culmination and termination of activity is still under debate. Here, in this paper, we shed new light on these questions by presenting for the first time a set of high precision $^{40}Ar/^{39}Ar$ isotope age data from Neogene volcanic rocks of this region.

The primary aim of this study was twofold, 1) to measure the age of samples from selected key locations where the present level of volcanological knowledge is sufficient enough to allow a significant step forward in our understanding of the timing and recurrence rate of the volcanism, and 2) to evaluate the existing K/Ar data set in comparison with the new $^{40}Ar/^{39}Ar$ ages.

2. Geological setting

Neogene intracontinental volcanic fields are present in the Pannonian Basin and consist mostly of alkali basalts and basanites Downes et al., 1992; Szabó et al., 1992; Embey-Isztin et al., 1993). Volcanism is thought to be related to extensional tectonics, and was shown to have developed along fault lines in the central part of the Pannonian Basin (Jámbor, 1989; Magyar et al., 1999). The volcanic centers in the Pannonian Basin are strongly eroded as the result of basin inversion since the Pliocene, and often only their root zones and feeding channels have been preserved (Conway et al., 1997). By size, inferred eruption mechanisms, distribution pattern, and erosion levels these volcanic fields are considered to be similar to other eroded monogenetic intracontinental volcanic fields such as the Hopi Buttes, Arizona (White, 1991). Volcanic features range from well preserved circular lava capped buttes that mark syn-volcanic paleosurface levels, to diatremes that indicate locations that are eroded up to hundreds of metres below the syn-volcanic paleosurface (Conway et al., 1997).

In western Hungary, two closely related volcanic fields are the focus of the present study (Fig. 1): the Bakony–Balaton Highland Volcanic Field (BBHVF) and the Little Hungarian Plain Volcanic Field (LHPVF). Though close to one another, the two fields show differences in preserved physical features; phreatomagmatic volcanoes in the northern LHPVF tend to be broader, lensoid landforms and peperites are common in their preserved crater/vent volcanic facies (Martin and Németh, 2005). The depth of magma — water interaction in these volcanoes is inferred to have been less than 300 m below the syn-volcanic paleosurface (Martin and Németh, 2004). The presence of peperites indicates that the host sediment (both siliciclastic and pyroclastic) into which the magma intruded or onto which lava erupted was water-saturated (Martin and Németh, 2005). In contrast, in the BBHVF, especially in the central and eastern part, large numbers of volcanic remnants exhibit features characteristic of magma-water interaction at deeper levels as e.g. in diatremes (Németh et al., 2001). In addition, there are two large shield volcanoes, Kab-hegy and Agát-tetõ respectively, in the northern part of the BBHVF. The location of volcanic vents is inferred to be related to the distribution of stream filled paleo-valleys as well as to ancient, probably rejuvenated pre-Neogene faults (Németh and Martin, 1999a).

The underlying basement to the volcanic fields in western Hungary largely consists of platform sediments belonging to the Alpine–Carpathian domain, which form a large anticline in the area of the Transdanubian

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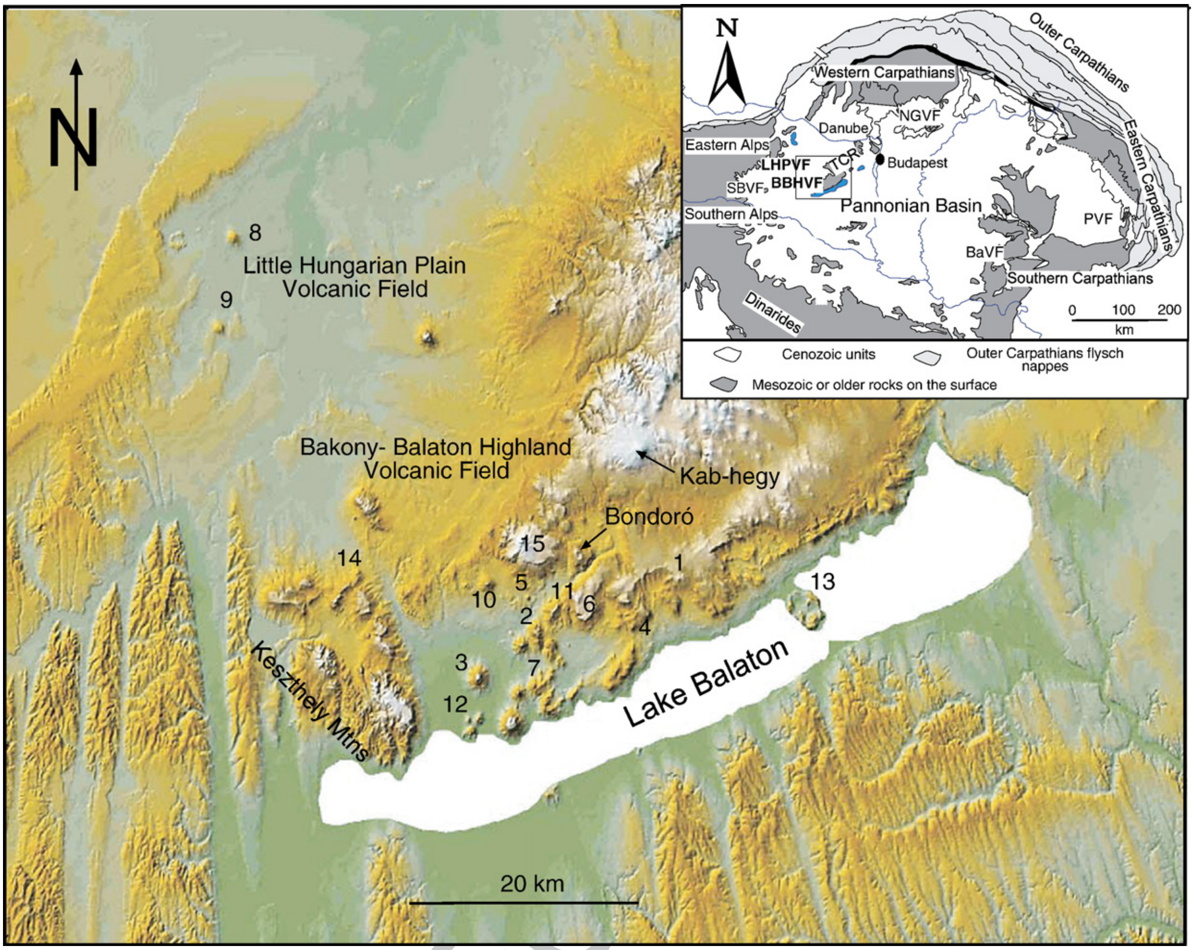

Fig. 1. Simplified geology map of the western Hungarian volcanic fields showing sites from where $^{40}Ar/^{39}Ar$ age determinations have been done; (1) Halomhegy scoria cone (HAL1) and lava flow (HAL2), (2) Hajagos maar filling lava lake (HAJ), (3) Szent-György-hegy lava lake (SztGY), (4) Hegyestû plug (HT-6), (5) Hegyesd diatreme (HD10), (6) Fekete-hegy maar crater filling lava lake (FH-4), (7) Tótihegy basanite plug/sill (TW13), (8) Ság-hegy tuff ring (SG2), (9) Kissomlyó tuff ring (KS-1), (10) Haláp maar (HA-1), (11) Füzes-tó scoria cone (FT7), (12) Szigliget diatreme (VAR) and coherent lava flow (SzgD), (13) Tihany Maar Volcanic Complex (TIH), (14) Sümegprága sill and dyke complex (SP), (15) Agár-tetõ shield volcano (AG1 and AG2).

Central Range (Martin and Németh, 2005). The oldest units consist of a thick package of Silurian schists, Permian terrestrial red sandstones and Alpine-type Mesozoic carbonate platform sediments. During the Neogene, immediately prior to initiation of volcanism, a large lake occupied the Pannonian Basin, the Pannonian Lake (Kázmér, 1990; Magyar et al., 1999) in which a thick sequence of siliciclastic sediments was deposited (Jámbor, 1989; Müller, 1998; Juhász et al., 1999). At the time volcanism began, the area was an alluvial plain (Magyar et al., 1999) on which shallow lakes existed and shallow subaqueous-to-emergent volcanism is inferred on the basis of the textures of pyroclastic rock units as well the common occurrence of peperites (Martin and Németh, 2005, 2007).

On the basis of unconformity-bounded continental sedimentary units in the Neogene stratigraphy of the western Pannonian Basin, three major maximum flooding surfaces have been identified and dated by magnetostratigraphic correlation at 9.0 Ma, 7.3 Ma and around 5.8 Ma (Lantos et al., 1992; Sacchi et al., 1999). The first maximum flooding event correlates with *Congeria czjzeki* fossils in lacustrine beds (Lörenthey, 1900; Müller and Magyar, 1992; Magyar et al., 1999), which mark the Lower Pannonian stage of Lörenthey (1900). After the flooding event, a significant base level drop and subaerial erosion took place around 8.7 Ma (Müller and Magyar, 1992; Sacchi et al., 1999). The second maximum flooding event took place around 7.3 Ma and it is considered to be represented by strata containing *Congeria rhomboidea*

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beds (Müller and Magyar, 1992; Sacchi et al., 1997, 1999). A general lowstand and subaerial conditions in the marginal areas is estimated to have occurred around 6 Ma (Sacchi et al., 1999), followed by the last known flooding around 5.3 Ma. On the basis of present knowledge, the ages of volcanic eruptions mostly postdate the latest highstand of the shrinking Pannonian Lake (i.e. younger than 5.3 Ma; Balogh et al., 1982, 1986) with the volcanoes erupted onto an erosion surface (Lóczy, 1913). Precise ages of volcanic rocks, and their correlation with the established eruptive history (subaerial versus shallow subaqueous/emergent) can provide important constraints for reconstruction of the sedimentary and landscape evolution of western Hungary since 9 Ma.

The western Hungarian volcanic fields form the eastern extent of a zone of Neogene intracontinental volcanism in central Europe that formed multiple volcanic fields, including the Massif Central in central France in the west, the Eifel volcanic field in the north and the Slovakian and Hungarian volcanic fields in the east. In western Hungary the formation of the Bakony – Balaton Highland volcanic field and the Little Hungarian Plain volcanic field resulted from 1) deep processes: melt supply from the lithospheric mantle, 2) crustal processes: the Pannonian basin itself was formed by early to mid-Miocene extension, and the volcanic field is situated in the northern block of the Balaton fault zone that is one of the major fault zones controlling the development of the Pannonian basin, and 3) surface processes: the water saturated near surface sediments in the late Miocene and Pliocene were the cause of the explosive character of most of the volcanic events.

3. Analytical techniques

The basalt samples were prepared using standard laboratory techniques (Koppers et al., 2001): following crushing and sieving 250–500 µm fragments were leached in dilute HNO_3 and HF in order to remove alteration phases. Any phenocryst phases present (plagioclase, clinopyroxene and olivine) were routinely removed before packaging ca 250 mg of groundmass in Al-foil packages. Sample packages and ca 5 mg aliquots of laboratory standard sanidine DRA-2 (25.26 Ma, intercalibrated against TCR-1 sanidine at 28.34 Ma; Renne et al., 1998) were sealed in 9 mm diameter quartz glass tubes, with one standard package positioned between every two packages of unknowns.

The irradiation of the tube was carried out for a period of 2 h in a standard 80 mm tall, 25 mm diameter high purity Al sealed tube inserted in a Cd-lined tube in the rotating RODEO poolside facility of the EU-JRC HFR reactor, Petten, The Netherlands, with the sample capsule positioned in the centre of the neutron field. The neutron flux profile across the reactor is optimized such as to give a negligible flux gradient across the central 12 cm of the Cd-tube. Rotation of the tube during irradiation (60 min^{-1}) helps to minimize the horizontal flux gradient in the tube. The correction factors for the Cd-lined RODEO tube were determined in numerous experiments in our laboratory using high purity Fe doped Ca-silicate and K-silicate glass at $(^{40}Ar/^{39}Ar)_K$: 0.00183±0.00010, $(^{39}Ar/^{37}Ar)_{Ca}$: 0.000699±0.0000001, and $(^{36}Ar/^{37}Ar)_{Ca}$: 0.000270±0.0000001).

Upon return to the laboratory, the standard minerals were loaded ca. 4–6 grains per position, (5 replicates for each position) in a Cu sample tray (diameter 66 mm, sample holes 2 mm diameter, 3 mm depth, 185 positions) in a low volume UHV gas sample purification line (Wijbrans et al., 1995) and fused by a laser single fusion technique under full software control. The laser beam, CW argon ion laser with principle lines at 488 nm and 514.5 nm and variable laser power up to 24 W in all lines mode, was focused to a ca. 200 µm spot size, and under software control, the x–y stage is moved in 4 circles increasing in diameter from ca 500 µm to 2000 µm to ensure that all individual crystals are fused using a ca. 15 W laser beam in the experiment. From each sample ca 50 mg was loaded in a Cu sample tray (diameter 66 mm, 22 sample holes of 6 mm diameter, 3 mm deep, and 60° angle to the wall to prevent laser shadows at the bottom of the pan). The rock fragments were spread out evenly in each position in the tray to ensure uniform laser heating. The laser beam was defocused to a ca. 2000 µm spot. The software controlled x–y stage moves the sample holder in a raster pattern (three runs right to left direction followed by three runs perpendicular to the first) under the laser beam to ensure event heating of the whole sample. Laser heating under these parameters lasted for 218 s, followed by 436 s clean time, which was sufficient to admit clean argon gas into the mass spectrometer. The 5 isotopes of argon (m/e: 40–36) and their low mass side baselines (at half mass distance) were measured sequentially by magnet field controlled peak hopping on an MAP 215-50 double focusing noble gas mass spectrometer fitted with a Johnston MM1 SEM detector operated at a relative gain of 500 with respect to the Faraday collector (10^{11} Ohm resistor on the Faraday collector amplifier). The SEM amplifier is fitted with three switchable resistors (10^9, 10^8, and 10^7 Ω), that will switch to an appropriate range after the ^{40}Ar beam intensity is measured during the peak centering routine at the beginning of each measurement. The integration time for each beam is variable at 1 s increments. Typical

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Table 1
Summary of $^{40}Ar/^{39}Ar$ age data from Neogene western Hungarian volcanic fields (single fusion results of an exploratory series are presented in the left columns; plateau ages and isotope correlation data for the incremental heating experiments in the centre and right columns. Full data tables are available in electronic format

Single fusion experiments				Incremental heating experiments							
		Age	±1σ	Plateau age	±1σ	MSWD	%39Ar, n steps	Inverse Isochron age	±1σ	MSWD	K/Ca±1σ
HAL1	VU45-A12	3297.9	±180.4	4.08	±0.05 ±1.11%	1.78	36.19 5	3.87	±0.17 ±4.47%	1.50	0.023±0.000
HAL2	VU45-A14	3903.8	±39.7	3.82	±0.03 ±0.74%	1.09	86.76 9	3.85	±0.04 ±0.11%	1.11	1.14%±0.002
HAJ	VU45-A15	3803.5	±40.6	3.80	±0.02 ±0.51%	1.91	71.71 7	3.74	±0.02 ±0.65%	0.76	0.246±0.004
SzgD	VU45-A17	3959.8	±47.2	4.53	±0.05 ±1.01%	1.64	79.68 9	4.33	±0.09 ±2.11%	1.01	0.120±0.002
SztGY	VU45-A18	4355.5	±24.6	4.22	±0.04 ±0.87%	1.68	86.57 9	4.14	±0.13 ±3.12%	1.60	0.286±0.004
HT-6	VU45-B2	7934.2	±47.4	7.94	±0.03 ±0.40%	1.86	46.22 5	7.78	±0.07 ±0.93%	0.37	0.075±0.001
HD10	VU45-B3	3671.4	±83.2	4.12	±0.01 ±0.33%	2.22	95.87 10	3.90	±0.10 ±2.46%	1.50	0.062±0.001
FH-4	VU45-B9	3857.9	±21.9	3.81	±0.02 ±0.49%	1.57	86.65 10	4.72	±0.03 ±0.66%	1.39	0.279±0.004
TW13	VU45-B11	4792.4	±25.3	4.74	±0.02 ±0.36%	1.91	90.51 9	4.72	±0.04 ±0.81%	1.98	0.207±0.003
SG2	VU45-B12	5543.8	±34.1	5.48	±0.01 ±0.26%	1.49	54.04 4	5.32	±0.18 ±3.42%	0.11	0.261±0.004
KS-1	VU45-B14	4569.5	±32.0	4.63	±0.02 ±0.34%	2.05	71.87 8	4.61	±0.02 ±0.45%	1.92	0.205±0.003
HA-1	VU45-B15	3162.2	±23.9	3.06	±0.02 ±0.51%	1.17	100.00 11	3.01	±0.03 ±0.84%	0.60	0.276±0.004
FT7	VU45-B17	2759.8	±38.7	2.61	±0.03 ±1.13%	1.20	91.65 10	2.52	±0.08 ±3.13%	1.12	0.106±0.002
VAR	VU45-B18	4171.5	±41.7	4.08	±0.02 ±0.59%	0.99	81.64 5	3.85	±0.47 ±12.30%	1.23	0.270±0.004
AG-1	VU51-B2	2998.1	±27.8 ±0.93%	3.00	±0.03 ±0.93%	1.60	99.02 9	3.14	±0.06 ±1.91%	0.98	0.100±0.024
AG-2	VU51-B3	3692.0	±38.8 ±1.05%	3.30	±0.03 ±0.80%	0.51	37.59 7	3.30	±0.04 ±1.11%	0.61	0.512±0.046
SP1861	VU51-B4	4153.2	±47.8 ±1.15%	4.15	±0.05 ±1.15%	0.85	98.88 9	3.81	±0.18 ±4.74%	0.37	0.025±0.009
TIH	VU51-B6	7987.0	±28.1 ±0.35%	7.96	±0.03 ±0.34%	0.51	75.89 5	8.01	±0.07 ±0.86%	0.46	0.164±0.043

settings are 10 s for ^{40}Ar and ^{39}Ar beams, 6 s for their baselines, 20 s for ^{36}Ar beams, and 10 for its baselines, the integration time on the ^{37}Ar beam is kept low (2 s) in order to avoid excessive increase in radioactive decay induced noise in the SEM. For data reduction we used the in-house developed ArArCalc2.2c software package (Koppers, 2002) (http://earthref.org/tools/ararcalc/). Mass discrimination was measured several times during the course of this project using our ^{38}Ar-air gas mixture (full description of our mass discrimination measurement protocol can be found in (Kuiper, 2003). For the decay constant and the abundance of ^{40}K we used the values recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1977). Using the values for flux monitors, decay constant and ^{40}K abundance discussed in this paragraph in the 2–8 Ma age bracket we are aware of a consistent bias of ca 1% towards younger ages between our isotopic measurements and the APTS developed for cyclically bedded Neogene sediments (Hilgen et al., 1999; Gradstein et al., 2004; Kuiper et al., 2004, 2005).

4. Results

High resolution $^{40}Ar/^{39}Ar$ laser incremental heating experiments were carried out on 18 samples from 14 locations in the western Pannonian volcanic province. Full data tables, age spectra, K/Ca spectra and isochrons can be found in a digital background data set (Background data set: Table 1), descriptions of the sample sites and dating results can be found in an appendix (background data set: Appendix). A summary of K/Ar ages published previously by Balogh and co-workers is included as Table 2 in the background data supplement. A summary of $^{40}Ar/^{39}Ar$ results is presented in Table 1 and in Fig. 2.

All experiments showed good consistent results with, in most cases, plateaus that meet commonly accepted reliability criteria. MSWD values were used to define the plateau segments (Koppers et al., 2001). All experiments yielded plateau segments with MSWDs indicating that the gas was derived from one isotopically homogeneous reservoir. For HD10 and KS-1 the calculated MSWDs were slightly higher then 2.0, as the result of low individual analytical step uncertainties. None of the samples showed significant amounts of excess or inherited ^{40}Ar in the non-radiogenic intercepts of the normal and inverse isochrons. Nor did any samples show evidence for profound overprinting subsequent to deposition, with the exception of sample VAR (from the Szigliget Vár-hegy pyroclastic succession) which nevertheless yielded an acceptable plateau age. Several spectra showed elevated ages in the initial steps which may either point to loosely bound excess ^{40}Ar or, alternatively, to recoil loss of ^{39}Ar from fine grained alteration phases (Koppers, 2002). Several experiments thus yielded mildly sloping inverse staircase spectra, step by step decreasing, still within acceptable limits forming a plateau, but perhaps indicative of mild alteration and consequent recoil loss over substantial parts of the gas release.

From the amounts of ^{39}Ar and ^{37}Ar released during the experiments some information may be obtained on the chemical composition of the mineral phases contributing to the spectrum. This effect, as shown in the K/Ca plots (see supplementary data tables), indicates that in the groundmass separates used for this study K-rich mineral phases consistently dominate during the first half of the experiment whereas towards higher experiment temperatures proportionally more gas is derived from Ca-rich phases. When the variation in K/Ca is larger than one order of magnitude, both end member phases contribute to the plateau age, which suggests that the K-rich phase observed in the first halves of the experiments is a primary magmatic phase and not an alteration product. The exception to this observation is sample AG2 (from a scoria cone remnant topping the Agár-tetõ shield volcano) where the phase enriched in Ca actually has a slightly, but in terms of finding a plateau, significantly increased age with respect to the plateau segment. The radiogenic component of the argon ranges from less then 10% to ca 80%. The low amounts of radiogenic argon typically found in the samples with low K/Ca is reflected in their proportionally larger analytical uncertainties (e.g. sample VAR).

5. Discussion

The new $^{40}Ar/^{39}Ar$ ages show that volcanism occurred in two broad periods: the first period is confined to two eruption centres formed along the north shore of Lake Balaton, Tihany and Hegyes-tû (Fig. 2, Episode I).

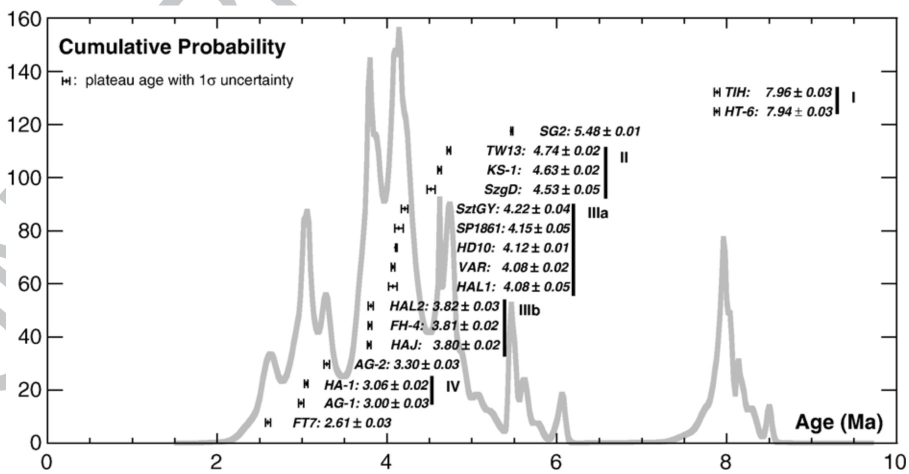

Fig. 2. Cumulative probability diagram showing all $^{40}Ar/^{39}Ar$ age information obtained for this study. All individual step ages and their 1σ uncertainties have been used to construct the cumulative probability curve in the diagram. Plateau ages and their 1σ uncertainty intervals are indicated as bars to the left of the individual ages. Age groups (Episodes I, II, III and IV) are identified with Roman numerals.

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The age results for these two centres, 7.94±0.03 Ma and 7.96±0.03 Ma are identical suggesting that we are dealing with two surface exposures of rocks from the same eruption. The other 16 samples (Fig. 3) define the second broad period of activity that formed of the volcanic field with eruptions starting ca. 5.5 Myr ago and reaching a culmination around 4.0 Ma (Fig. 2) with activity recorded at Halom-hegy: 4.08, 3.82 Ma, Hajagos: 3.80 Ma (Fig. 3a), Hegyesd: 4.12 Ma, Fekete-hegy lava field: 3.81 Ma, the Szigliget diatreme Vár-hegy pyroclastic sequence: 4.08 Ma, and the Sümegprága sill: 4.15 Ma). This second broad period ended ca 2.6 Myr ago.

In addition to the broad division into two periods, the first centred around 8.0 Ma and the second centred around 4.0 Ma, it was noted that eruptions in different

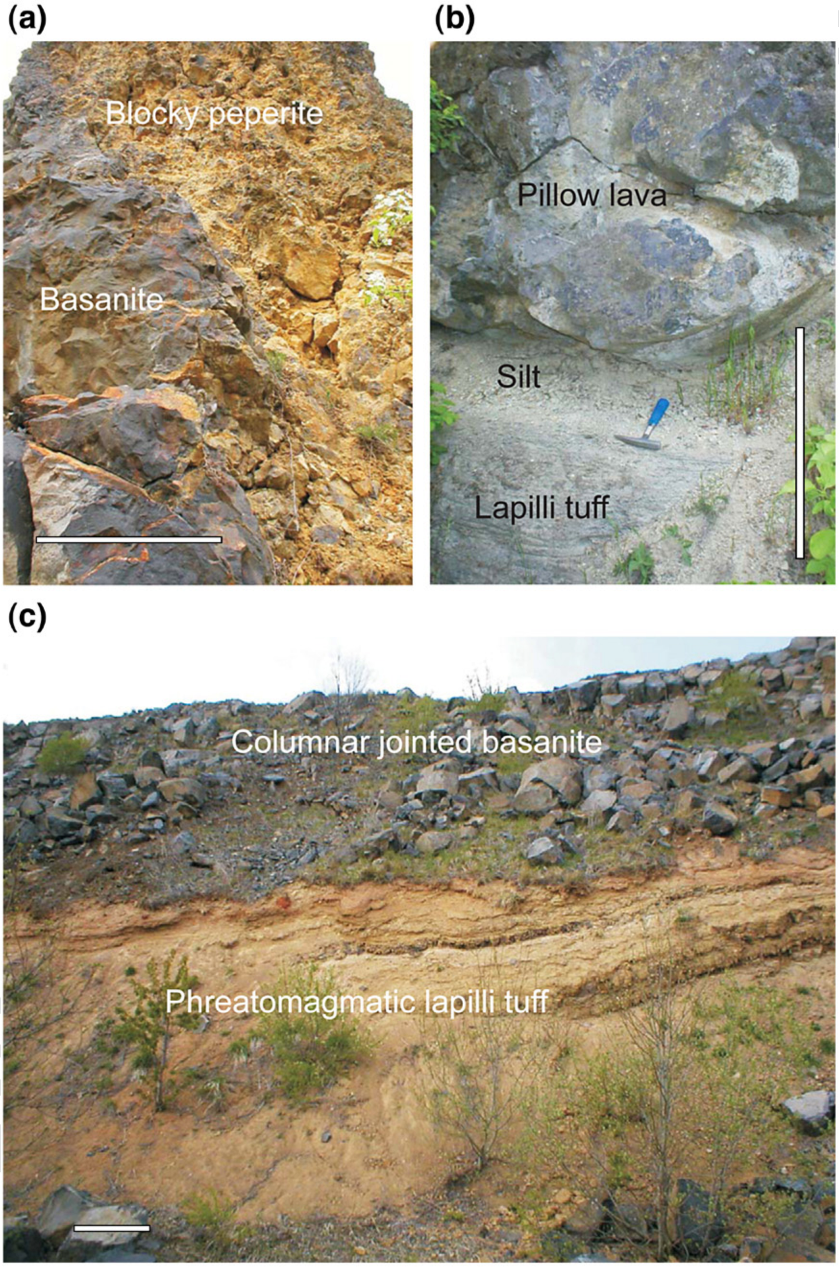

Fig. 3. Measured samples from a) dated blocky peperite from Hajagos (Location 2). Dark angular clasts are the basanite hosted in fine sediment; b) Kissomlyó (Location 9) pyroclastic unit overlain by siliciclastic beds invaded by the dated lava, c) columnar jointed basanite overlain the tuff ring units at Haláp maar (Location 10). White bars represent 1 m on each figure.

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volcanic centres often yielded age results that were indistinguishable. This observation forms the basis for dividing volcanic activity of the field into 5 distinct episodes (I, II, IIIa, IIIb and IV). These episodes are defined as periods of activity yielding tightly clustering ages, often within the individual 2 sigma uncertainties of the plateau age results. Three ages, that of SG2 (5.48 ± 0.01 Ma), AG-2 (3.30 ± 0.03 Ma, and FT7 (2.61 ± 0.03 Ma) have not been shown as occurring in different centres.

The oldest ages from our ^{40}Ar/^{39}Ar geochronology were derived from a basanite plug of Hegyes-tû (7.94 Ma) and the Tihany volcano (7.96 Ma), together defining Episode I. These ages are in excellent agreement with the 7.92 Ma K/Ar age of the Tihany maar volcanic complex (Balogh and Németh, 2006), and represent the oldest ages from the western Hungarian alkaline basaltic volcanic fields. These ages fall in the time between the maximum highstands of the Pannonian Lake at 9.0 Ma (msf-2) and 7.3 Ma (msf-3) (Sacchi et al., 1999). A lowstand characterized by erosion and widely exposed marginal lake banks is inferred to have developed around 8.7 Ma ago (Sacchi et al., 1999). The ages of Hegyes-tû and Tihany (this work, Balogh and Németh, 2005) suggest, that these volcanoes erupted in the phreatic zone of the Pannonian Lake, near to its shoreline, where water to sustain phreatomagmatism was likely available from the large water mass of the nearby lake (Németh et al., 2001). The likely paleogeomorphological scenario would be similar to that of the Newer Volcanics in Victoria, Australia, or the Recent Ukinrek Maars formed in the 1977's in Alaskan Peninsula, Alaska where volcanic fields have developed in a near shore environment (Self et al., 1980; Johnson, 1989; Jones et al., 2001).

The main activity during the younger period occurred around 4.0 Ma (Episode III). On the basis of the plateau results this group might be subdivided into an older sub group (episode IIIa) and a younger subgroup (episode IIIb). The isochron results would suggest that all these eruptive products belong to one single group. The Szigliget diatreme age is relatively poorly determined, due to a low level of radiogenic ^{40}Ar* and consequent larger error in the dating results. The significance of the similarity of these ages is, that the large lava field of the Fekete-hegy can be viewed as a marker horizon, a ca. 3.81 Myr old paleosurface preserved by the lava. The Fekete-hegy lava flow has a contact with pyroclastic rock units at an altidue of ~340 m a.s.l., similar to that at Hajagos (~320 m level contact with pyroclastic rocks), and to the altitude of the uppermost deposits of the pre-volcanic siliciclastic succession. Taking these values into account, and inferring a fairly uniform paleosurface over the area of the field would imply that the topmost exposures of the Hegyesd and Szigliget diatremes (~260 m and ~220 m a.s.l., respectively) still would be around 80–100 m below the syn-volcanic paleosurface. This estimate is in good agreement with volcanological observations and the interpretation that these two sites represent exposed diatremes (conduits of former phreatomagmatic volcanoes). The total thickness of pre-volcanic, mostly Pannonian (Upper Miocene) sand and silt eroded since these volcanoes erupted 3.8–4.2 Myr ago would be around 200–250 m, implying a 50–65 m/Myr long term averaged erosion rate for these sites. Szent György-hegy with an age of 4.22 ± 0.4 Ma is the oldest centre with activity during this period. These estimates are in the same range as those inferred previously on the basis of volcanic facies analyses and published K/Ar ages (Németh and Martin, 1999a).

The volcanic vents belonging to Episode III are associated with phreatomagmatic pyroclastic units interpreted as evidence that the magma interacted with abundant water (Németh and Martin, 1999b). The textural characteristics of the pyroclastic sequences indicate that phreatomagmatic explosions took place below a subarieal paleosurface, i.e. not under lacustrine conditions (Németh and Martin, 1999b). The great variety of peperite at Hajagos (Fig. 3A) (Martin and Németh, 2007) suggests, however, that sufficient amounts of water were present in a near-surface aquifer to fill the maar basins created by the explosive eruptions. In these water-filled basins, newly erupted basanite melt interacted with the water saturated wall-rock, crater wall, and pre-volcanic mud and silt to form various peperites (Fig. 3a) (Martin and Németh, 2007). The age of Fekete-hegy and associated sites corresponds well with the proposed time at which the Pannonian Lake dried up (Sacchi et al., 1997, 1999; Magyar et al., 1999; Sacchi and Horváth, 2002), and thus is consistent with the observation of subaerial magmatism in combination with a water-saturated, near surface, aquifer. Conditions at this time were still substantially wetter then present day conditions in the area.

A group of volcanoes, designated as belonging to Episode II is slightly older then the Fekete-hegy and associated sites on the basis of the ^{40}Ar/^{39}Ar ages grouping around 4.5 to 4.8 Ma (Szigliget lava: 4.53 Ma, Kissomlyó: 4.63 Ma and Tóti-hegy: 4.74 Ma: Fig. 2, Episode II). Of this group the Szigliget lava sample should be viewed with some caution. The field relationships between the Szigliget pyroclastic sequence (4.08 Ma) and the coherent lava body (4.53 Ma) are unclear. An intrusive contact of the lava was proposed (Borsy et al., 1986) because of its oblique, non-uniform

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thickness and because both the underlying and overlying rock is pyroclastic rock with very similar textural features. However, the new age data make this interpretation problematic, and instead indicate a 'normal' layer cake stratigraphy, with an older lava flow overlain by a younger phreatomagmatic pyroclastic succession. Alternatively, Szigliget may represent an erosional remnant of a nested diatreme. In this reconstruction, the age data derived from the pyroclastic rocks and the coherent lava body document two different phreatomagmatic events which occurred about 0.5 Myr apart. The coherent lava body and its host pyroclastic unit in this interpretation should belong to an older diatreme, within which a new diatreme developed. Similar nested diatremes are not unknown, especially from kimberlite fields (Skinner and Marsh, 2004), and, therefore, the new age dating suggests that further research on Szigliget with aimed at understanding its volcanic evolution, is required. One should be cautioned however that the Szigliget samples, especially the cauliflower bomb sample from the capping pyroclastic unit, are from basalt that is particularly low in potassium and hence had a very low enrichment in radiogenic ^{40}Ar. Therefore the analytical uncertainty of its ages is large and, thus, the two ages might still belong to the same event.

The ^{40}Ar/^{39}Ar ages of Szent György-hegy: Kissomlyó and Tóti-hegy seem to indicate an eruptive period from 4.2 to 4.8 Ma, which overlaps in time with the period when the Pannonian Lake progressively decreased in size (Sacchi et al., 1999). The age of the lava lake infilling the Kissomlyó tuff ring (Fig. 3b) is 4.63 Ma by the ^{40}Ar/^{39}Ar method. This age is significantly younger than that of the nearby (5.48 Ma) Ság-hegy lava, and, therefore, assuming coeval initiation of volcanism in the Kissomlyó–Ság-hegy area, it can be interpreted as the age of a lava which erupted from the same volcano that produced the Kissomlyó tuff ring. Although all these volcanoes belonging to the 4.2–4.8 Ma period erupted in subaerial conditions, the widespread evidence of phreatomagmatism is considered strong evidence for the abundance of water in the rocks near the Earth's surface at this time. The presence of peperite, intra-crater lacustrine sediments, and glassy volcanic textures may reflect surface water involvement in the development of the Kissomlyó volcano and suggest that shallow (few metres) standing water bodies may have developed from time to time on the large flat plain of western Hungary (Martin and Németh, 2005).

The oldest age (5.48 Ma) for the volcanic field in the younger age group was derived from a peperitic sill from Ság-hegy. This age is correlated with the last lowstand of the Pannonian Lake, however, the pyroclastic succession and intrusive bodies of Ság-hegy clearly demonstrate that they developed in a wet environment. From this observation we argue that after the Pannonian Lake ceased to exist, the first few 100s of metres of the stratigraphy remained water saturated for several millions of years. Thus, after the retreat of the Pannonian Lake, the resultant alluvial plain most likely was littered with small alluvial lakes reflecting a generally high water table and fluctuating in extent with seasonal and climatic variations.

The youngest ^{40}Ar/^{39}Ar ages were found for the Agár-tetõ shield volcano (AG1: 3.00 Ma), the Haláp tuff ring (3.06 Ma) (Fig. 2, Episode IV) and the Füzes-tó scoria cone (2.61 Ma). The relatively young ages of these localities indicate that their morphology may partly preserve their original volcanic structure. At Haláp, the dated lava flow caps the phreatomagmatic pyroclastic sequence of a tuff ring (Fig. 3c). The lava flow and the pyroclastic sequences have a peperitic contact suggesting that the tephra ring must have been water saturated, therefore, a water-filled crater is inferred. At Haláp no original volcanic landform can be recognized. At Füzes-tó the young age is supported by its well-preserved central depression filled with ballistic bombs and lava spatter indicating that its crater is still intact and unbreached. It is notable that after 2.61 Myr of erosion Füzes-tó still has kept its form, which suggests slow erosion rates and/or that local factors prevented excessive erosion. A young K/Ar age of 2.3 Ma has been measured from Bondoró (Fig. 1), a volcano that is similar to Füzes-tó; however, its crater has been breached (Embey-Isztin, 1993). A similar young age has also been derived from Agár-tetõ, a capping scoria cone remnant, giving an age of 2.98 Ma by the K/Ar method (Balogh et al., 1982). It seems that the closing stage of the volcanism in western Hungary was around 2.5–2 Ma.

In terms of magmatic processes the Western Hungarian volcanic fields are characterized by several episodes during which (near-) synchrononous eruptions occurred at multiple centres. This observation is interpreted as evidence for a discrete number of melt emplacement events during which melt generated in the sublithospheric mantle was emplaced into the crust. The amounts of magma were sufficient to feed several edifices, but not enough to sustain prolonged magmatism at individual edifices. Although we have identified discrete episodes of magmatism, there is no evidence for periodicity in the data. i.e. from our data we cannot deduce that magmatic events occurred with a predictable frequency: the time span between the onset of magmatism at 7.97 Ma and the second event is 2.5 Myr, the period between the second and third episode is ca 700 000 yr, and between the second and third episodes between 4.65 Ma and 4.10 Ma

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was 550 000 yr, and between the final episodes between 3.80 and 3.00 Ma was ca. 800 000 yr.

Several authors have suggested that there is a relation between magmatism and basin extension in the Pannonian Basin (Horváth, 1993). The main phase of basin extension in the Pannonian Basin, however, predates the development of the West Hungarian volcanic fields. The onset of magmatism at ca 7.95 Ma in fact occurred during a period of relative quiescence in the basin evolution, and the main phase of magmatism around 4.0 Ma coincides with the onset of basin inversion (Cloetingh et al., 2005; Fodor et al., 2005). While basin inversion was probably responsible for the disappearance of the Pannonian lake in the early Pliocene, there is no clear evidence that it caused the episodes of mantle melting recorded in the volcanic fields of western Hungary. During the early stages of inversion the environment was still wet enough to cause the phreatomagmatic features in the volcanic field, but it is probably significant that one of the shield volcanoes in the area, Agát-tetõ, is in fact one of the youngest features in the field, and formed after basin inversion had largely dried out the area.

6. Conclusion

When comparing the existing data set of conventional K/Ar ages with new high resolution $^{40}Ar/^{39}Ar$ ages for the volcanism in the western Hungarian alkaline basaltic, intracontinental volcanic fields, we may conclude that the two methods yielded consistent results, provided that the samples are simple groundmass samples with limited alteration and limited excess ^{40}Ar or extraneous ^{40}Ar contained in phenocrysts. The similarity has confirmed that in an absolute sense the timing of the Neogene volcanic events inferred for the Bakony–Balaton and Little Hungarian Plain volcanic fields is correct. However, in addition, we demonstrate the potential of $^{40}Ar/^{39}Ar$ dating for establishing volcanic stratigraphies for individual centres. The significant difference between the two methods is the analytical uncertainty, which is an order of magnitude less for $^{40}Ar/^{39}Ar$ dating, and the more consistent check for sample homogeneity. However, as we are dealing here with the products of explosive volcanism, some of the material used for dating was highly fragmented during formation: some of the fragments can easily be recognized as bombs formed upon eruption, but other fragments particularly in diatremes and scoria cones cannot easily be characterized by morphology. In such cases it may not be possible to distinguish syn-extrusive bomb fragments from shattered intrusions from deeper down in the plumbing system. Thus, the real geological problems may cause a larger range in expected ages and thus the increased precision of the $^{40}Ar/^{39}Ar$ method also should be complemented with more and more focused field research in order to interpret the isotopic results.

The $^{40}Ar/^{39}Ar$ ages confirm that:

(1) Volcanic activity peaked around 4 million years ago during perhaps 2 periods of intensified activity that affected several centers. The older Tihany–Hegyes-tû period at 7.95 Ma was of more limited importance, both in areal extent and in volume of magmatism.
(2) Volcanism occurred near-synchonously at multiple locations at four times during the history of the volcanic field: first at ~7.95 Ma (n=2, at Tihany and Hegyes-tû), at ~4.1 Ma (n=5, at Halom-hegy, Szent György-hegy, Hegyesd, Vár-hegy, and Sümegprága), at ~3.8 Ma (n=3, at Halom-hegy, Hajagos, and Fekete-hegy), and at 3.0 Ma (n=2, at Agár-tetõ, and Haláp).
(3) There are no clear spatial patterns in the distribution and timing of volcanism in western Hungary, There may have been though a slight east to west shift in the location of vents with time.
(4) The very low analytical uncertainties of the $^{40}Ar/^{39}Ar$ dates allow us to distinguish volcanic events at closely spaced centres to provide better understanding of rejuvenation of volcanic eruption centres at the same place (Kissomlyó vs. Ság-hegy), and may also be used with success to confirm more prolonged activity at individual sites, and thus may cast doubt on whether this type of volcanism is truly 'monogenetic'.
(5) The dated volcanoes erupted at a time of lowstand in the nearby Pannonian Lake, and despite the abundant evidence to support a water-rich eruptive environment (Ság-hegy, Kissomlyó, Tihany) these volcanoes are inferred to have erupted in a subaerial phreatic zone adjacent to the lake itself.

7. Uncited references

Q1

Bada and Horváth, 2001
Horváth and Tari, 1999
Webb et al., 2004

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jvolgeores.2007.05.009.

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